Abstract. This paper presents practical implementation of computer support for an effectiveness analysis of queue algorithms in flexible manufacturing systems (FMSs). A proposed model, based on hierarchical timed coloured Petri net (HTCPN) formalism, is used as a simulation instrument. Implementation of various queue methods has been successfully deployed and tested: due time, minimum makespan, maximum makespan, minimum time reserve and random queue as a reference solution. This comprehensive study of the given queue algorithms investigates the interference with order completion time, global production time and machine loading problems. As a result of conducted studies, based on simulation model, the estimated ratio of effectiveness, described as the criterion fulfilment of production system controlled by the given algorithm, for each of the proposed queue methods has been presented as well as further possible improvements proposals.

Keywords: Petri net, queue algorithm, flexible manufacturing system, FMS.

1. Introduction

The planning of manufacturing processes appeared to be of a significant importance in terms of flexible manufacturing systems (FMSs) when production changes rapidly and is strongly focused on customers’ demands. The computer supported modules for effective planning and queuing orders, which are constantly coming from customers, are indispensable elements of such modern FMSs. The need for using a computer support does not only result from the willingness of being up-to-date in comparison to competition but it is also connected with complexity of significant tasks which an enterprise has to face in economically unstable environment. Regardless of company’s activity in service or production field, the usage of sophisticated IT systems does not only stimulate rapid reactions to ever changing business environment but also allows to predict how resolved decisions will affect the future prosperity of an enterprise. [1, 2, 3]
The range of problems related to event prediction in business reality is an extremely complex issue but also absorbing at the same time. Modern implementations of IT systems which provide support in decision making processes (Decision Support Systems - DSS) are applicable, among others, in Business Intelligence (BI) software class, which is often implemented as a part of advanced Enterprise Resource Planning (ERP) systems [1]. With regards to production enterprises, where manufacturing processes are crucial for business continuity, making decisions without any previous analysis, in extreme cases may lead manufacturing processes to a deadlock. In order to provide a supportive tool in decision making process on this level, one should reach for professional IT solution called Advanced Planning and Scheduling (APS) system. This software can be considered as a subsystem of ERP or as an additional module which extends functionality of Manufacturing Execution System (MES). [4, 5, 6]

Production planning with decision support, which is provided by APS, is essential in modern manufacturing when FMS systems are considered with short batches, agile manufacturing or variant production and all of the above multiply complications. For in opposite to traditional planning, actual range of regarded factors is extended significantly. Therefore the object of the latest production planning systems is not only a proper sequence of actions planning but to develop efficient strategy which will evolve with the time and will be depend on current production indexes, variable market demands, costs or time preferences, balanced job coverage or machine loading indicators. In a such compound work environment any act of decision making, usually results in deterioration of the secondary indicators in a given time horizon. [4, 7]

One of the key subsystem in APS solution is an order’s queue management system. Sequence of orders delivered to production may have significant impact on tardiness of orders, overall time of production and even on machines malfunctions. Due to the aims assigned during production scheduling process, there are possibilities to create queues to minimalize overall production time, minimalize tardiness or to maximalize machine utilization. This narrow scope of production scheduling problem will be introduced in following points of this paper and simulation studies will determine how order queue sequences influence specific production indicators. Petri net formalism used in conducted studies has been verified in many research projects. [8, 9, 10, 11, 12]

2. Description of the issue

Queuing production orders in advanced APS systems are proceeded in a dynamic way. This means, the important issue is the time when we analyze a current order list. The factors which should be considered at a given time, among others are: status of orders in production, a list of completed orders or predicted availability of machines, materials and personnel. Nevertheless, every advanced production system is forced to freeze some of the incoming orders in a given time horizon. That situation takes place just before the order or order list is placed into production zone and is called frozen zone. One of the reasons for using such a method is the fact that all machines involved in production process may require time-consuming tools changeovers. Defining properly assorted frozen zone allows to prepare technological instrumentation for proceeding the orders from this zone. Another asset of the zone is a psychological feeling of predictability for employees, which provide
the time for operational planning in production. Considering presence of frozen zone idea in production scheduling systems, a decision has been made to proceed with queuing of orders against chosen method and to place an output list of orders in a frozen zone. Orders from created list are transferred consecutively to production zone, unless a destination workstation is occupied. Orders being proceeded in production zone have higher priority than orders in frozen zone.

![Simplified schema of production system](image)

**Figure 1. Simplified schema of production system**

In Figure 1. presented is a list of incoming production orders, outgoing production orders and four workstations: M1 – Lathe, M2 – Miller, M3 – Grinder, M4 – Quality Control. Also, possible transport directions during production process are shown.

**Table 1. Description of order lists adopted for research purposes**

<table>
<thead>
<tr>
<th>List number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A pack of ten orders elaborated from actual production data. Characteristic feature in this list is presence of six orders following technological route RT6 and one order with long processing time in comparison to other orders.</td>
</tr>
<tr>
<td>2</td>
<td>A pack of ten orders created for investigation of simulation system behaviour in case of balanced machine utilization, balanced technological routes usage and with comparable processing times for all orders.</td>
</tr>
<tr>
<td>3</td>
<td>A pack of ten orders created for purpose to investigate simulation model in case of two orders with long processing time with balanced usage of all available technological routes.</td>
</tr>
<tr>
<td>4</td>
<td>A pack of ten orders created by an expert. The main purpose of this list is to provide maximum diversity of order’s sequence depending on queue algorithm. The intention is to provoke extremely different simulation results for just one order list.</td>
</tr>
</tbody>
</table>

Every order collected in the incoming list can realise one of seven possible technological routes:

- Technological route RT1: M1 – M4,
- Technological route RT2: M2 – M4,
- Technological route RT3: M3 – M4,
- Technological route RT4: M1 – M2 – M4,
• Technological route RT5: M1 – M3 – M4,
• Technological route RT6: M2 – M3 – M4,
• Technological route RT7: M1 – M2 – M3 – M4.

Furthermore, all orders should be completed before a given due time, defined by technology-construction department and confirmed by customer.

For research purposes, four specific production order lists have been adopted. In each of them ten production orders have been defined. Details on each order list are shown in Table 1.

In order to set a sequence of production orders that are available on incoming list, which is going to be put to a frozen zone, definite sorting algorithm has to be used. Five chosen algorithms are described below:

• Algorithm based on randomness – for each order from the list, a different number from 1-10 range is drawn. The numbers indicate the sequence of entering into production zone for each order. After a drawing and conducted simulation, the results are saved. Simulations are repeated for fifty times for each list and average result for each list is treated as a reference point for other algorithms,

• Due time algorithm – list of orders is searched for an order with a closest due time, such an order is designated as number 1. As a result of further searching, successive order is designated as number 2. The last searching designated number 10 to an order with the most distant due time,

• Minimal makespan algorithm – sorting of lists is dependent on the total sum of times needed for proceeding on every machine and is sequenced from the shortest one,

• Maximal makespan algorithm – sorting of a list is dependent on the total sum of times needed for proceeding on every machine and is sequenced from the longest one,

• Minimal time reserve algorithm – sorting is done on the basis of minimal time reserve factor described as:

\[ Trc = Tzk - Tobr, \]

where:
- \( Trc \) – time reserve value,
- \( Tzk \) – due time of order,
- \( Tobr \) – sum of times needed for proceeding on every machine,

and the sorting itself is done from the lowest, to the highest \( Trc \) factor.

3. Simulation model

In order to construct a simulation model, IT tool named “CPN Tools” has been used. This software allows to build advanced systems on the basis of HTCPN with usage of Standard Meta Language (SML).

One of the essential features of coloured Petri net is its ability to assign colours to tokens, considering that fact, specific construction of order’s token has been proposed:

\[ (s, rt, t1, t2, t3, t4, dl, ord), \]

where:
- \( s \) – numbers from 1-10 range, determining the sequence for entering production zone,
- \( rt \) – numbers from 1-7 range, determining technological route of order,
- \( t1 \) – numbers from 0-4000 range, determining proceeding time on workstation M1,
t2 – numbers from 0-4000 range, determining proceeding time on workstation M2,
t3 – numbers from 0-4000 range, determining proceeding time on workstation M3,
t4 – numbers from 0-4000 range, determining proceeding time on workstation M4,
dl – numbers from 200-9000 range, determining due time for order,
ord – identification (external) number of order.

The value of variable “s” is assigned during queuing orders, whereas the value „ord” is inherited from superior system and all other attributes are assigned by technology-construction department.

Considering the feature of hierarchical Petri net, the whole model has been divided down to three layers, shown in Figure 2.

**Figure 2. Hierarchical construction of simulation model**

Main Layer is responsible for selecting next order from the list and depending on workstations’ statuses, grant or deny the entry of selected order to production zone. Production Sublayer, the mid-layer of the net, is responsible for proper processing on workstations 1, 2 and 3 with correct priority and technological routes constraints. Quality Control Sublayer, the lowest layer of the net, is a modelling quality control station.

The third specific feature of HTCPN is the time. Considering time implications in the examined model, two methods are involved: global simulation clock analysis and individual time stamps of tokens analysis. The analysis of individual time stamps of tokens allows, for instance, to determine the work time of each workstation and then after correlation with global simulation clock, to define machines utilization coefficients.
4. Simulation studies

In the first stage, simulation studies have been conducted in order to determine the reference values. For each of four order lists, with random generator included in the software, fifty drawings of orders sequences have been made. Quality of random generator has been verified experimentally and the results are shown in Figure 3.

![Number of routes drawn per 10000 samples in CPN Tools](image)

**Figure 3. The number of routes drawn per 10000 samples in CPN Tools**

The scope of collected data for each order list consists of:

- average overall production time,
- average workstations’ utilization coefficients,
- average number of delayed orders,
- average sum of delayed time of all orders.

Having obtained reference values, the core simulation studies involving selected queue algorithms application for each order list have been consequently conducted. Graphical representation of the results is shown in the following figures.

Figure 4 shows the impact on overall production time of selected queue algorithm. Experiment was performed on four different order lists.
By taking overall production time into consideration, the advantages of maximal makespan algorithm emerged. With this algorithm, the maximal shortage of overall production time was reached in three of four order lists. The difference between the best and the worst available solution equals 28%.

Figure 5 shows the impact on machine utilization coefficients of selected queue algorithm. Experiment was performed on four different order lists.

In case of machine utilization analysis, there is no single preferable queue algorithm that will match all four order lists. The highest machine utilization coefficient for order list 1 was obtained with minimal time reserve algorithm. For order list 2 - the best available solution appears to be minimal makespan algorithm and for order list 3 - due time algorithm and minimal time reserve algorithm. In case of order list 4 the highest machine utilization coefficient was obtained by using minimal makespan algorithm.

Promptness of orders in production process is extremely important issue which can be described by various parameters and helps to estimate the effectiveness of queue
algorithms. Figure 6 shows the impact on number of delayed orders of selected queue algorithm.

Implementing a due time algorithm and a minimal makespan algorithm resulted in the lowest number of delayed orders. Correlation between algorithms and number of delayed orders, order list 4 is the one which draws our attention the most. This only proves that using specific queue algorithm leads to elimination of delayed orders, what surely would impress our customers. Another aspect worth emphasising is the fact that the maximal makespan algorithm, pointed as one of the fastest, causes simultaneously maximal number of delayed orders. Except for order list 4, in which elimination of delayed orders is possible, all other cases indicate that difference ratio among selected algorithms reaches 67% of the number of delayed orders.

Figure 7 shows the impact on sum of tardiness in order list 1. This list consists of ten random production orders elaborated from actual production data. A characteristic feature of this list is the presence of six orders following technological route RT6 and one order with long processing time in comparison to other orders.

**Figure 6. Selected queue algorithm impact on number of delayed orders**

**Figure 7. Selected queue algorithm impact on sum of tardiness in order list 1**
In case of order list 1, considerable differences in the sum of tardiness were observed, depending on the algorithm used. Disparity between the best available solution and the worst reached 97%. In this particular instance, due time algorithm proved its usefulness. Figure 8 shows the impact on sum of tardiness in order list 2. This list consists of ten production orders, which are evenly distributed in technological routes and have designated similar proceeding times.

![Figure 8. Selected queue algorithm impact on sum of tardiness in order list 2](image)

For order list 2, similarly as for order list 1, the lowest value of the sum of delayed times is assigned to due time algorithm. In this case, maximal time difference between selected algorithms reached 90%.

Figure 9 shows the impact on sum of tardiness in order list 3. This list consists of ten production orders, where two of them are distinguished by long processing times in comparison to other.

![Figure 9. Selected queue algorithm impact on sum of tardiness in order list 3](image)

Taking into consideration the obtained results for order list 3, the most effective way to queue this list appears to be minimal makespan algorithm, which decreased the tardiness by 91% in comparison to the worst solution - maximal makespan algorithm.
Figure 10 shows the impact on sum of tardiness in order list 4. This list consists of ten production orders, which are comparatively variant in technological routes and in defined proceedings times designated to work stations.

![Bar chart showing the impact of different queue algorithms on sum of tardiness in order list 4.](chart.png)

**Figure 10. Selected queue algorithm impact on sum of tardiness in order list 4**

For order list 4, as the only one, the possibility to avoid tardiness of production process has been proved. Three queue algorithms were able to neutralise the time: due time, minimal makespan and minimal time reserve.

5. **Conclusion**

The above studies indicate that the queue algorithm used for sequencing production orders has a significant impact on the effectiveness of production systems. A detailed analysis of the obtained results leads to the conclusion that the maximal makespan algorithm allows to reach the highest machine utilization coefficients and ipso facto, accompanied by the shortest overall time of production. Unfortunately, the application of this algorithm resulted in the longest delays in proceedings of individual orders. The implementation of the due time algorithm, on the other hand, allowed to reduce the number of delayed orders to minimum. Nevertheless, in this instance, machine utilization coefficients failed to reach such a high value. In particular events, when the minimal time reserve algorithm was used it was clearly visible that the number of delayed orders decreased. With regards to the process of focusing the enterprises on unconditional customer demands satisfaction where time is a crucial factor, the usage of the last algorithm shall be considered as the most preferable.

Arriving at the conclusion, which has been based on implemented queue algorithm, various goals have been accomplished - shortage of overall production time, improvement of the machine utilization coefficient also lowering the number of delayed orders and reduction of the sum of delayed times. In further works, the issue of automatic selection of the best algorithm is planned to be solved in correlation with order list parameters and status of production system. In order to achieve this goal, the authors intend to implement methods based on fuzzy reasoning and genetic algorithms.
References